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Study on a cascade pulse tube cooler with work recovery

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Abstract

On the basis of traditional single stage pulse tube cooler, a cascade pulse tube cooler is designed and fabricated which includes a primary and a secondary stage pulse tube cooler connected by a transmission tube which recovers the acoustic power from the primary stage. In this paper, the transmission tube and the secondary cooler are optimally designed. Cooling power of 207.9 W is obtained in the preliminary experiment, which is higher than the maximum cooling capacity 189.6 W of the single stage cooler, which demonstrates our concept.

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Keywords: Cascade PTC; Work recovery; SAGE; 233 K; Simulation; Experiment;

1. Introduction

With the development of high temperature superconductor(HTS), such as superconducting transformer, superconducting generators, superconducting motor and superconducting cables, higher requirements are proposed for high power cryogenic coolers with cooling capacity up to hundreds of watts[1].

Pulse tube cryocooler(PTC) has no moving parts at the cold end, it has advantages of free vibration, long life, simple structure and high reliability and has been an international hotspot in related fields in recent years[2]. However, the acoustic power at the cold end could not be recovered by the displacer or piston like Stirling cryocooler, instead, it is dissipated in the resistance of an impedance network at the warm end of the pulse tube, thus

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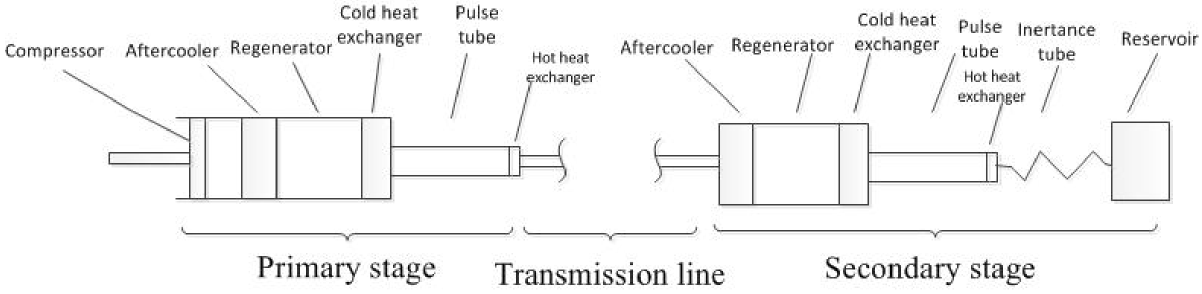

Fig. 1.Schematic diagram of the cascade PTC

its highest coefficient of performance(COP) is limited by T_C/T_H, other than Carnot efficiency $T_C/(T_H-T_C)$ [3]. It is worthless to recover the work dissipated for cryocoolers with small cooling capacity or working at very low temperatures, while for large coolers with $T_C \sim T_H$, the recovery is of great significance.

G.W. Swift [4] proposed a configuration of PTC which could recover the acoustic power by introducing a quarter-wavelength tube to replace the pulse tube and the hot end heat exchanger, so that the transformed oscillation at the outlet of this tube is suitable for driving another cooler. Different from recovering work directly at the cold end, in this paper, a new structure (as shown in Fig. 1) which recovers work at the hot end of the pulse tube was proposed based on the following two considerations. Firstly, the pulse tube, acting as a thermal buffer, can isolate the heat transfer between the cold and hot ends. Secondly, the sudden area changing from regenerator to transmission tube may cause extra losses and jet flows [5]. The most important issue we consider is that our approach retains the original structure of the PTC, simply adding a transmission tube to drive another PTC; thus, it makes the improvement of an existing PTC possible.

Because the acoustic power available at the cold end heat exchanger is always less than T_C/T_H times the driving power, it is hardly worth recovering at the lowest Tc. Moreover, in order to avoid problems of inhomogeneity inside the regenerator so that we can put our attention on the credibility of work recovery, 233 K is chosen as the cooling temperatures for the two coolers.

The primary stage had been fabricated and tested [6], results showed that the acoustic power dissipated at the hot end of the primary stage is more than 200 W with 500 W electric input power, which is worthy to be recovered. A detailed simulation process of the secondary stage pulse tube cooler with work recovery was presented, and the experiments on the cascade cooler were carried out to demonstrate our basic idea.

2. Optimization of the transmission tube and the secondary stage

The primary stage PTC unit is an existing structure, the cascade PTC model is built and stimulated based on software SAGE [7],with the parameters of the primary stage specified. The mean pressure is 2.5 MPa, the cold temperature is 233 K, and the frequency is 60 Hz, the parameters of the transmission tube and the secondary PTC are optimized to get the highest COP of the whole unit.

2.1. Transmission tube

It is not suitable to drive a secondary pulse tube cooler with the oscillating volume flow rate lagging the oscillating pressure, so a transmission tube is used to adjust the phase angle between oscillating volume flow rate and the oscillating pressure at the hot end of primary stage. The design goal of the transmission tube is not only to ensure the proper phase angle at the inlet of the secondary stage, but also to lower the dissipation losses as much as possible along the tube.

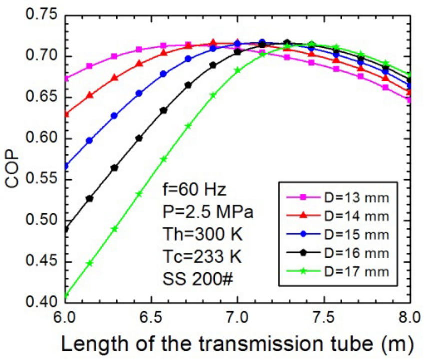

Fig. 2.COP versus parameters of the transmission tube

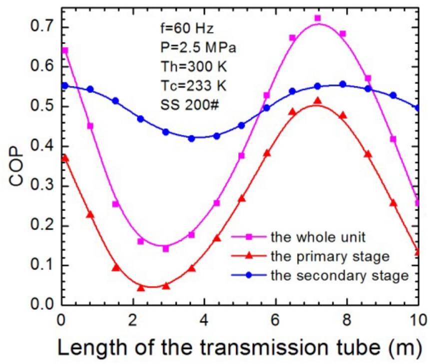

Fig. 3. COP versus the length the transmission tube

Fig .2 shows how the diameter and length of the transmission tube influence the performance of the cascade PTC. For a given diameter, there is always an optimal length to maximize the COP and this length increases as the diameter goes up with the maximum COP. A copper tube with diameter 14.2 mm was chosen as the transmission tube. Fig. 3 shows how the length of the tube affects the performance of the primary stage, the secondary stage and the whole unit when the tube diameter is fixed at 14.2 mm. With the change of length, the three curves develop with sinusoidal fluctuations and the primary stage fluctuate more wildly than the secondary stage, which illustrate the great influence of the length on the phase angle of the primary stage so that influence the performance of the whole unit. When the length of the tube is less than 10 m, there are two optimal length (0 m ,7 m respectively). 7 m is chosen because the COP is slightly higher than that of 0 m.

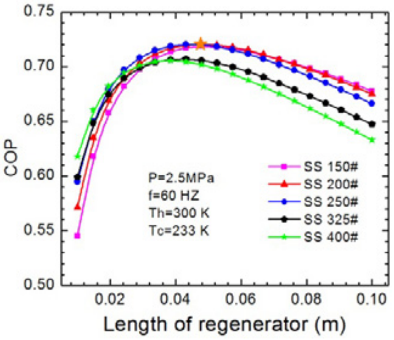

Fig. 4. COP versus the length of regenerator and matrix

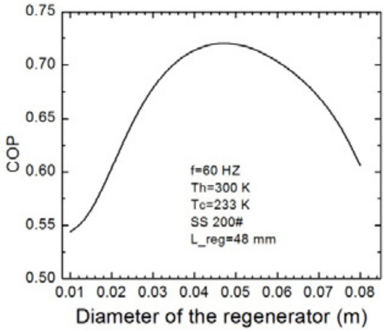

Fig. 5. COP versus the diameter of regenerator

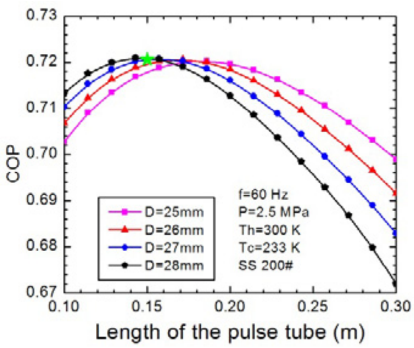

Fig. 6. COP versus the length of pulse tube

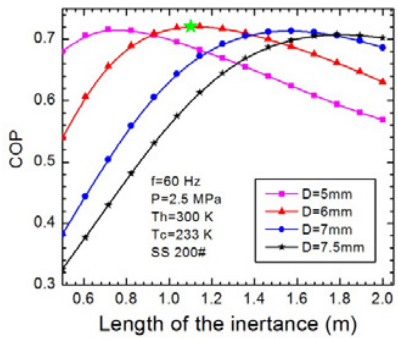

Fig. 7. COP versus the length of inertance tube

2.2. Regenerator(II)

Regenerator is the core part of a PTC filled with matrix like stacked fine-mesh screens or packed spheres to store heat during the cycles. The function of the regenerator is to transmit a given acoustic power from the compressor to the cold end with minimum losses. The mesh of the matrix, the length and the diameter of the regenerator were optimized with Sage.

The relationship between COP and mesh is presented in Fig. 4 and the 200# mesh is chosen to optimize other parameters for its high COP. Optimizing the length of the regenerator is to compromise the enthalpy flow loss and the pressure drop loss. Also, the length of the regenerator is decided by the frequency and the cold temperature, the optimum length would be shorter when the frequency is higher, and it will be longer when cold temperature is lower. 48 mm is chosen as the length for its highest COP with the optimal mesh.

Fig. 5 shows the relationship between the diameter and the COP when the length is fixed at 48 mm, and the best performance is achieved when the diameter is 47.6 mm.

2.3. Pulse tube(II)

The pulse tube is an open tube which transmits acoustic power in an oscillating gas system from one end to the other across a temperature gradient with a minimum of power dissipation and entropy generation. The acoustic power transmitted is the namely highest possible cooling power. For a given diameter, pulse tube has its own optimum length and this length decreases as the diameter goes up as shown in Fig .6. In the pulse tube with small length-diameter(LD) ratio, the stroke of the gas piston is short which makes the cooler uneasy to modulate the phase. Furthermore, the inhomogeneity of the mass flow and temperature distribution will get intensified as the diameter of the pulse tube goes up. 27 mm is chosen as the diameter of the pulse tube with the optimum length of 150 mm and a big LD ratio (>5).

2.4. Inertance and reservoir

An inertance tube and a reservoir are designed to make the mass flow and the pressure in phase at the middle of the two regenerators, which is conducive to minimizing the dissipation of the acoustic power in the regenerator and achieve the best performance. After simulated observation, 1 L is chosen as the most suitable volume for the reservoir. Fig. 7 shows the influence of the length and diameter on the performance of the cooler, for a given diameter, the inertance tube has its own optimum length and this length increases as the diameter goes up. It is obvious that the maximum COP of the cooler with inertance tube diameter of 5 mm, 6 mm and 7 mm do not have much difference. 6 mm is chosen with the optimum length of 1.1 m.

2.5. Results of the optimization

Table 1. Results of the optimization

Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
Frequency	60	Hz	Pressure	2.5	MPa
L_reg (II)	47.6	mm	D_reg (II)	48	mm
L_pt(II)	150	mm	D_pt(II)	27	mm
L_it	1.1	m	D_it	6	mm
L_transmission tube(II)	7	m	D_transmission tube(II)	14.2	mm
Mesh no.	200	#	Vr	1	L

The designed size of each part is listed in Table. 1.

2.6. Theoretical analysis of the cascade PTC

With the optimized parameters, Table 2 shows the simulation results of the single stage PTC and the cascade PTC, 189.6 W@233 K cooling power of the single stage is obtained theoretically. While under the same working condition, the cooling power is increased from 189.6 W to 243.63 W and the COP can be raised by 30% from 0.553 to 0.718. What's more, the pressure ratio at the cold end of the primary stage is decreased from 1.182 to 1.138 with cooling power decreased from 189.6 W to 175 W, this sacrifice is made for enhancing the transmission of the acoustic power from the primary stage, improving the cooling performance of the secondary stage so that the COP of the whole unit is maximized.

Table 2. Comparison on simulation results of the cascade PTC and the original single stage PTC

Parameters	**Original single stage PTC**	**Cascade pulse tube cooler**		
		Primary stage	Secondary stage	Whole unit
Frequency	60 Hz	60 Hz	60 Hz	60 Hz
Mean Pressure	2.5 MPa	2.5 MPa	2.5 MPa	2.5 MPa
Pressure ratio at the cold end	1.182	1.138	1.118	-
Input electrical power of comp.	500 W	-	-	500 W
Input PV power	379.5 W	364.8 W	126.6 W	364.8 W
Cooling power	189.6 W@233 K	175 W@233 K	68.63 W@233 K	243.63 W@233 K
Coefficient of performance	0.5531	0.5154	0.5423	0.718
Relative Carnot Efficiency	15.9%	14.8%	15.6%	20.6%

3. Experimental setup

Fig. 8. (a) is the three-dimensional model of the cascade PTC. Fig. 8.(b) is the picture of the real structure, which includes the primary stage PTC unit, the transmission tube and the secondary stage PTC unit. The two stages include after cooler, regenerator, cold end heat exchanger, pulse tube, hot end heat exchanger respectively. Both coolers are thermally insolated by pearlite.

Three rhodium-iron resistance thermometers were installed in the cold end heat exchanger of the primary stage and two platinum-resistance-thermometer were installed in the cold end heat exchanger of the secondary stage for temperature measurement.

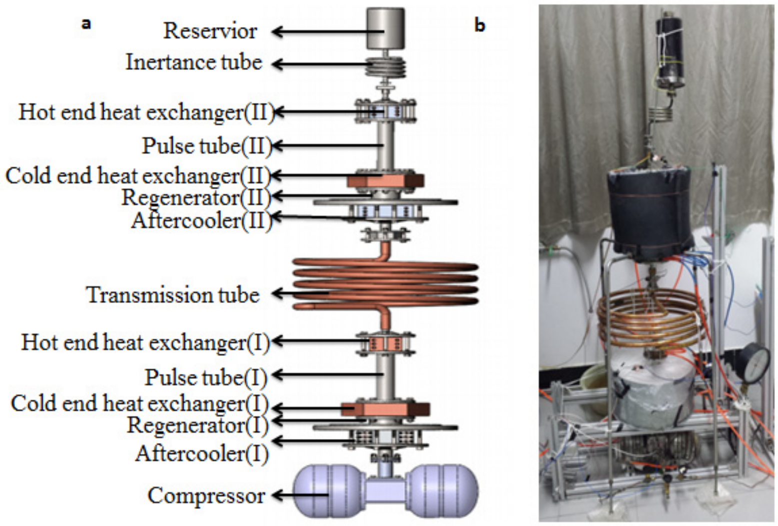

Fig. 8. (a) three dimensional structure; (b) real product.

4. Experimental results

With an electric input power of 500 W, charging pressure of 2.5 MPa, frequency of 60 HZ. Fig. 9 is the cooling curve line of the cascade pulse tube cooler, It shows that the cooling rate of the secondary stage is slower than the primary stage which got the lowest temperature 119.0 K with less than 200 min and kept at 123.3 K finally. The secondary stage got the lowest temperature 131.0 K with more than 500 min because of the huge cold sink shown in Fig. 8.

Cooling capacity of the primary and the secondary stage is also tested, 145.0 W for the primary stage and 62.9 W for the secondary stage are obtained when both of the temperature are at 233 K, the summation of which is higher than the theoretical cooling power 189.6 W@233 K of single stage PTC.

Fig. 10 presents the comparison of the prediction of Ladner [8], single stage PTC results and our cascade PTC results. When the temperature is at 233 K, our cascade PTC obtains the COP of 0.42 and the fraction of Carnot efficiency 0.12, which is much better than Ladner's prediction line.

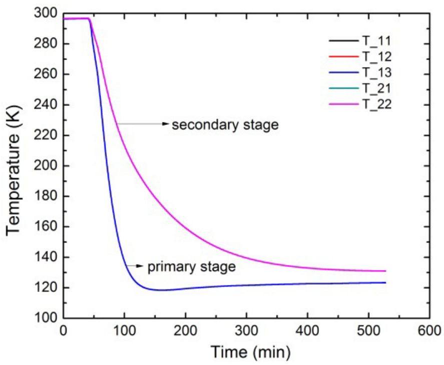

Fig. 9. Cool down curve of the PTC

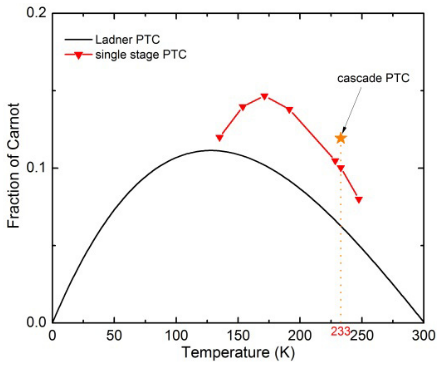

Fig. 10. Cooling performance of the PTC

5. Conclusion

A cascade pulse tube cooler model, which consists of a primary stage, a transmission tube and a secondary stage, is built to recover the work dissipated in the resistance of an impedance network.

The experimental data turned out to fit well with simulation results. Simulations showed that 246.1 W@233 K cooling capacity of the cascade PTC could be obtained compared to 189.6 W@233 K of the single stage PTC under the same working condition. Experiments were carried out with 207.9 W@233 K of cooling capacity obtained, which is even higher than the stimulated results of the single stage PTC. The basic concept of work recovery PTC is verified and is expected to be useful for high power cryocoolers working at lower temperatures.

Acknowledgements

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